MADYMO MODELING METHOD OF ROLLOVER EVENT AND OCCUPANT BEHAVIOR IN EACH ROLLOVER INITIATION TYPE

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ABSTRACT

The purpose of this research was to understand the differences between vehicle and occupant kinematics for the various forms of rollovers. In particular the occupant kinematics in the initial phase of the rollover was studied, which is critical in determining the restraint system activation timing.

Six rollover tests were conducted consisting of six initiation types; FMVSS 208, SAE J857, corkscrew, curb trip, soil trip, and ditch rollover. From this test data MADYMO models were constructed of the vehicle and occupant. The test data included the influence of gravity, therefore, a method to adjust for the influence of gravity was developed for the MADYMO models.

The vehicle model were validated using curb trip and SAE J857 tests. The compensation procedure for the influence of gravity was also confirmed. Once the vehicle model was validated using the two test modes, each of the other test modes were simulated and the dummy head behavior was compared to the actual test data.

From the simulation results and the actual test data the differences in the occupant kinematics for each of the rollover initiation types was compared.

INTRODUCTION

Various methods for vehicle rollover testing have been proposed.

Larson [2000] et al, proposed a sled test with the Rollover Coaster Dolly (RCD).

Wu [2000] et al, introduced various rollover test modes for the restraint system development, Critical Sliding Velocity test, Curb trip test, Corkscrew ramp test and SAE J2114 test (FMVSS 208).

The NASS database classifies the rollover initiation types in 6 patterns; Trip-Over, Flip-Over, Turn-Over, Climb-Over, Fall-Over and Bounce-Over.

In this research, we conducted rollover tests that includes each of the six types listed by NASS for the coverage of real-world rollover accidents as thoroughly as possible.

Hughes [2002] et al, introduced an alternative rollover testing procedure based on the FMVSS 208 dolly test. Hughes asserted that the dynamic rollover testing was non-repeatable.

To develop an effective restraint system to protect occupants in rollover accidents it is necessary to have a repeatable test.

Balavich [2002] et al, studied the influence of the vehicle lateral acceleration on occupant kinematics in a trip over test condition using sled testing. However, there are various initiation types in real-world rollover accidents in addition to the trip over condition, in which the occupant kinematics must also be understood. The simulation model provides a tool that can be used to evaluate restraint system technology in the various forms of rollover initiations with repeatable results.

TEST METHODS

In this research, NISSAN conducted 6 types of rollover initiations.

1.) FMVSS 208 Test / SAE J2114 Dolly test.

The test vehicle was positioned on the dolly at an angle of 23 degrees. The dolly was then accelerated to 30mph and stopped suddenly. As the dolly was stopped the vehicle continued in the lateral direction at 30mph until the wheels contacted the ground, initiating the rollover.

Figure1. FMVSS 208 test.

2.) SAE J857 Test

This rollover test procedure was outlined in SAE standard number J857 (this procedure has been abolished by SAE). The vehicle was accelerated by a tow system to the desired test speed. Once it was released from the tow system the steering system was turned to full lock using a hydraulic cylinder attached to the steering system. Once the steering reached full lock the inboard wheels went over a ramp positioned in the trajectory of the vehicle. The combination of the centrifugal force generated from the steering input and the vertical force inputed from the ramp generated a roll moment inducing the vehicle to rollover. The test procedure outlined in J857 recommends using a guide rail installed on the ground to provide the steering input. However, as noted we used a hydraulic cylinder to control the vehicles steering system, which allowed us vary the steering angle, the steering rate, and vehicle trajectory.

Figure2. SAE J857 test.

3.) Corkscrew Test

The test vehicle was propelled in a straight longitudinal direction with a ramp installed on the right side of the vehicle. As the vehicle was released from the tow system the right hand tires of the vehicle went over the ramp inducing a roll moment in the test vehicle causing it to rollover.

Figure3. Corkscrew test.

4.) Curb Trip and Soil Trip Tests

We used a decelerator sled method to simulate both the curb and soil trip conditions. The test vehicle was positioned laterally on a sled dolly with the lead wheels positioned against a steel curb on the dolly. The sled dolly was then accelerated to the desired test speed, at which time a set of brakes on the sled were activated to stop the sled dolly. As the dolly decelerated the vehicle reacted against the steel curb inducing a roll moment causing the rollover. The brake settings were varied depending if curb or soil trip was being simulated. A lower deceleration level with a longer duration was used to simulate the soil trip condition. The test vehicle was tethered to the sled dolly so that it could not rotate more that 90 degrees, allowing the vehicle to be reused.

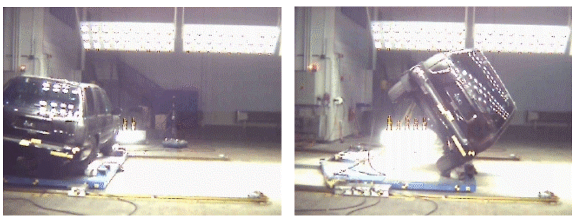

Figure4. Curb trip and Soil trip test.

5.) Ditch Test

The ditch test simulates a driver veering off the road and going into a ditch, and trying to recover by steering up the incline of the ditch.

The test was setup such that as the vehicle was released by the tow system it went over an incline that was setup to be 10 degrees from the longitudinal axis of the vehicle. The angle of the incline could be set to be any angle between 30 and 50 degrees in 5 degree increments. As all four tires entered the incline the vehicle's steering system was actuated to steer the vehicle up the incline. The combination of the gravity component acting along the lateral axis of the vehicle on the incline and the lateral acceleration generated by the steering input induced the vehicle to rollover.

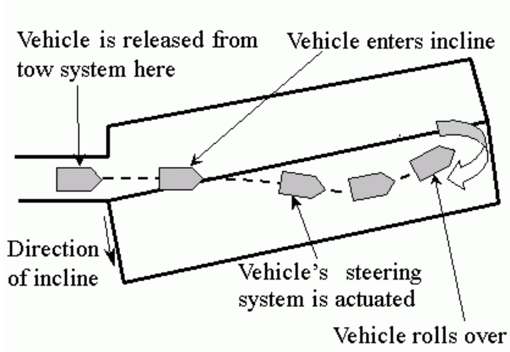

Figure5. Ditch test.

Hybrid III dummies were positioned at each front outboard seating position and onboard cameras were positioned on the test vehicle to allow analysis of the dummy kinematics during the rollover. The test vehicle was instrumented to measure the X, Y, and Z acceleration and the X, Y, and Z axis angular velocity at the vehicle's center of gravity. This data was used in creating the MADYMO models.

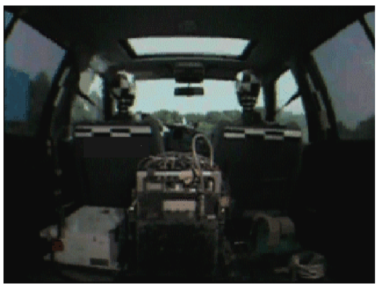

Figure6. Video angle of high speed video camera in the test vehicle.

Rollover accidents tend to have a much longer duration than other types of accidents. For example the duration of a frontal impact is approximately 150 milliseconds where as a rollover can have duration of up to six seconds or more depending on the velocity and number of rolls. In our testing we concentrated on the initial quarter turn of the rollover for the initial occupant kinematics; which had a maximum duration of 2.5 seconds. In the ditch test, 2.5 second was needed because the vehicle was carried by inertia to the incline after the vehicle was released

from tow system.
Given the long duration that we were trying to model we chose MADYMO software with its multi-body modeling, which provides short calculation times, and provides well correlated dummy models of the Hybrid III dummy.
We used the data collected at the vehicle C.G. as the input for which provided the prescribed motion to the vehicle MADYMO model. This allowed us to accurately model the kinematics of the vehicle's occupant compartment without having to model the vehicle suspension and tire characteristics, greatly simplifying the model.
Due to the large roll and pitch angles experienced by a vehicle in a rollover the influence of gravity on the accelerometer data is large and must be accounted for in the MADYMO model. A method was developed to determine the influence of gravity using MADYMO, and separate that influence from the raw data. This procedure used only the vehicle and consisted of three steps

Step 1
The test data was adjusted for any offset using the pretest data. We then added 9.8 m/sec^2 to the measured test data to the Z acceleration component. A MADYMO simulation was conducted using the test data at the vehicle CG. This data was inputed as the vehicle local coordinate system in the MADYMO model. In the rollover tests the vehicle's local coordinate system rotates with the vehicle. Therefore, it was necessary to use angular acceleration as well as the linear acceleration of the vehicle as inputs in the model. The angular acceleration was determined by taking the derivative of the angular rate data collected from the tests.
A rigid body representing the test vehicle with a moment of inertia, mass, and initial velocity that matched the actual test vehicle was positioned at the CG of the vehicle (matching the measurement point in the rollover tests). An ellipsoid shape to represent the vehicle was connected to the rigid body. This ellipsoid is only for visual aid and does not have any functional contact interaction. The vehicle model used is showed in figure7.

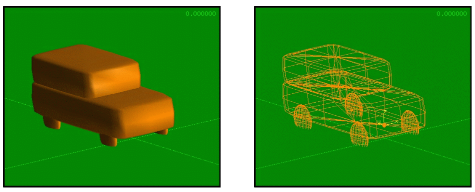

Figure7. Simple vehicle model.

Step 2
In the first step we added the influence of gravity to only the Z channel, however in the test data the influence of gravity is dispersed throughout the event. Therefore, to isolate the influence of gravity in the simulation the global linear acceleration (X, Y, and Z directions) was provided as an output of the simulation. In the global coordinates the influence of gravity will only be seen in the vertical component (Z direction). We subtract 9.8m/s^2 from the Z axis data of Step1 simulation which was outputted as global coordinate data. This process can provide the data of pure vehicle kinematics except the gravity influence. About the other axis data, we can use the data of linear acceleration of X axis and Y axis and angular acceleration of 3 axis without any process as the input data of Step3.

Step 3
The vehicle kinematics are calculated again using the global coordinate system data determined in step 2. The following data were used as the inputs for the MADYMO model in the global coordinate system:
- X axis linear acceleration
- Y axis linear acceleration
- Z axis linear acceleration, minus influence of gravity
- Angular velocities about X, Y, and Z axies

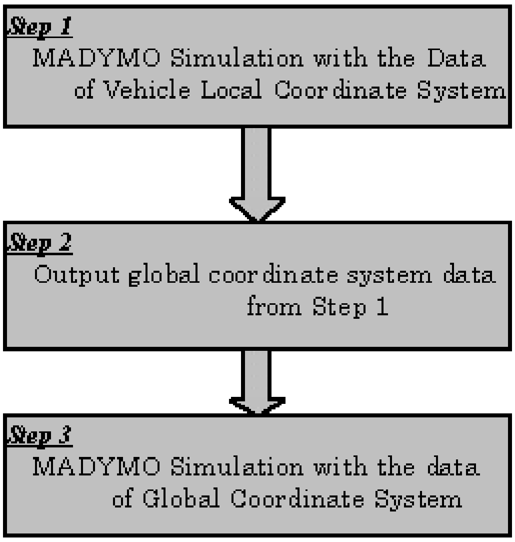

Figure8. Procedure to pick up the pure vehicle rollover movement from the test data.

Simulation Result: Vehicle Motion
Figure9 and 10 show the simulation result of the SAE J857 test with the vehicle turning to the right and going over the test ramp.

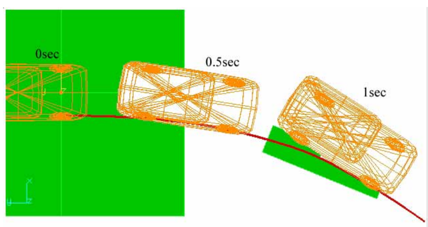

Figure9. Vehicle behavior of simulation in SAE

J857 type – plan view-.

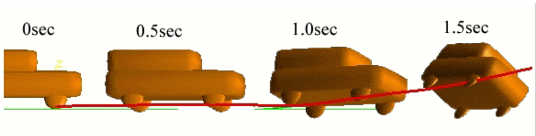

Figure10. Vehicle behavior of simulation in SAE J857 type – side view-.

In the figure9 and figure10, red line shows the trajectory of front right wheel. This trajectory is measured in the actual test for the validation of simulation model. Figure11 shows the comparison of that trajectory between the simulation and the actual test in the plan-view. Based on this the model was judged to be well correlated to this test pattern.

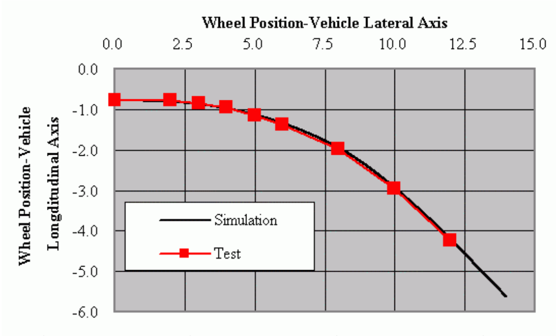

Figure11. Trajectory comparison about the vehicle front right wheel.

Next we applied this technique to the trip over test, to confirm the reliability of this procedure. Figure12 shows the animation of trip over simulation.

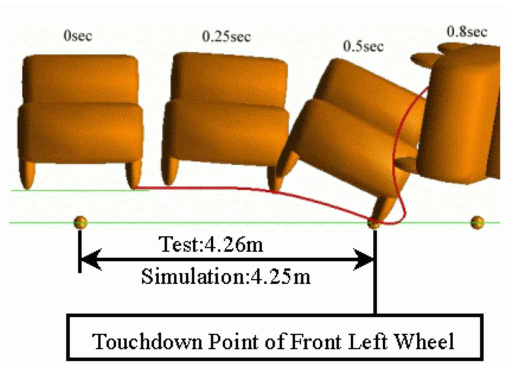

Figure12. Simulation result of trip over test.

Figure13. Actual vehicle behavior in trip over test.

The distance that the wheel touched to ground after launching from sled is 4.26m. It was measured by the slip mark on the ground. The simulation result was the 4.25m. It shows that this procedure could be applied to the trip over test as well as the SAE J857 test.

As the influence of the suspension and tires on vehicle body kinematics was ultimately represented by the vehicle CG data such as linear acceleration and angular rate collected in the rollover test, this data was used in this simulation. This method greatly reduced the model complexity and simulation run time in MADYMO.

INTERIOR AND OCCUPANT MODELING

Next, we constructed the interior model for the simulation of the occupant kinematics.

The following items were included in the model of the vehicle interior do to the occupant interaction with them.

Seat / Door Trim / Floor / Floor Tunnel

Seat-Belt / Side window

Figure14 shows the model that was constructed.

The following items were also included in the model as visual aides, however, no contact interactions are defined for these items.

Tires / Roof Panel / Pillar Trim / Steering wheel

The actual test data is used to define the contact interaction characteristic between seat and the dummy; which has great influence on the dummy kinematics during the initiation of a rollover event. The seatbelt model uses the MADYMO conventional belt system to shorten the modeling time.

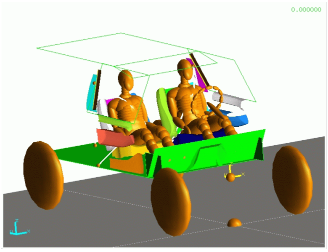

Figure14. Interior and dummy model.

Using this interior and dummy model and the test data, we conducted a simulation of each rollover test. Figure15 shows the animation of the simulation of the SAE J857 rollover.

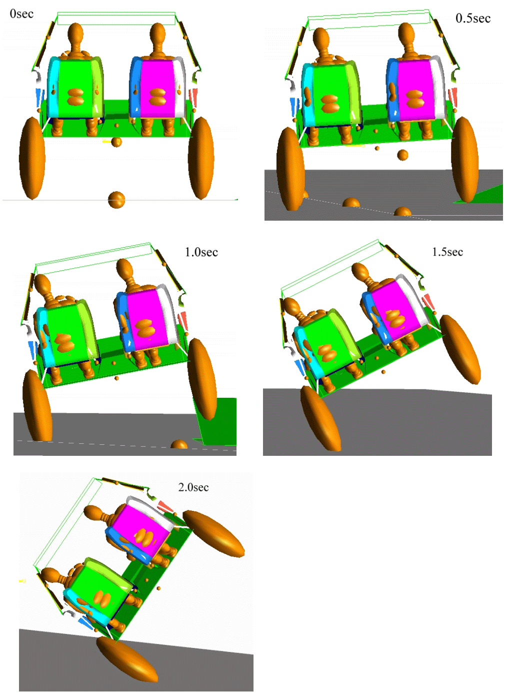

Figure15. Occupant simulation result of SAE J857 type.

Comparing the dummy head kinematics between the model and the actual test validated the dummy kinematics in the model. We did this by digitizing the test film from the onboard cameras and comparing those results to the results from the simulation.
The dummy head trajectory was calculated in the simulation using the vehicle local coordinate system, allowing easy comparison with the actual test data.
The simulation for each rollover initiation type was run until the vehicle reach a roll angle of approximately 90 degrees. Table 1 lists the specific roll angle and simulation duration for each of the rollover initiation types modeled. The ditch test exhibited the longest duration. This was because time zero in this test was defined as release from the tow system. After release from the tow system the vehicle continued in a straight line carried by its inertia before entering the incline after which point the rollover was initiated. Time zero in SAE J857 and corkscrew were also defined as release from the tow system. After release from the tow system, the vehicle continued to run before the vehicle ran onto the ramp. In the FMVSS208, curb trip and soil trip test, the time zero was defined as the starting point of sled deceleration.

Table1. Simulation time and roll angle in each test types

	Simulation Time[sec]	Roll Angle[deg]
SAE J857	2.5	109.6
Corkscrew	1.5	123.9
Ditch	2.8	131.3
FMVSS208	1.0	196.0
Curb-Trip	1.0	77.4
Soil-Trip	1.0	91.2

DISCUSSION

- MODEL ACCURACY

Figures 16, 17, 18, and 19 show the simulation result of curb and soil trip, SAE J857 and ditch rollover tests. As this data shows the dummy head movement on the near side (the side towards the rollover initiation) of the vehicle correlates well with the test data.

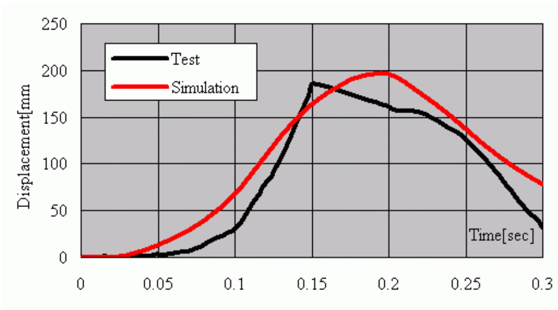

Figure16. Head movement of the near-side dummy in curb trip type.

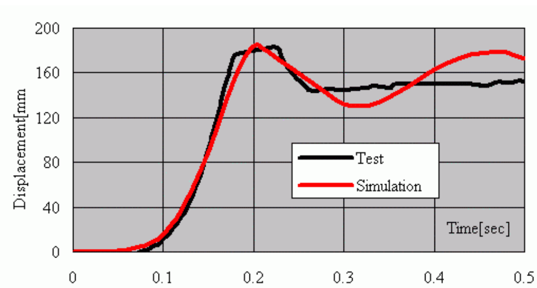

Figure17. Head movement of the near-side dummy in soil trip type.

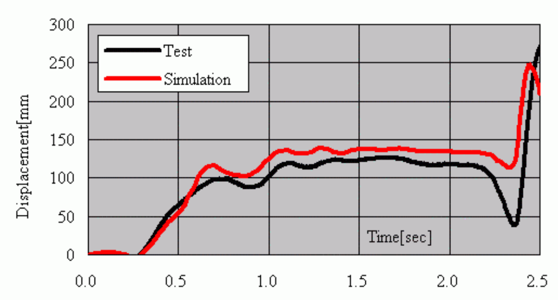

Figure18. Head movement of the near-side dummy in SAE J857 type.

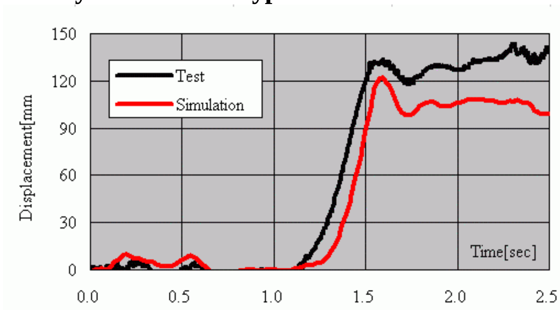

Figure19. Head movement of the near-side dummy in ditch type.

When comparing the occupant head displacement between the simulation and the test data in curb trip simulation (Figure16), there was some variation between the two. Comparing the film of the actual test and the simulation result, it appears that the stiffness of the seat frame is one of the factors to be considered in this variation. The seat frame was not included in the model; only the stiffness of the seat cushion was modeled.

There were striking differences between the simulation and the test data for the kinematics of the far side occupant in corkscrew simulation. The MADYMO seatbelt model used for this research, which is stitched to the dummy's chest, is intended for front impact modeling. While this does not negatively influence front impact modeling, in a rollover the far side occupant tends to slide out from under the shoulder belt. Since the MADYMO seatbelt is stitched to the dummy it does not allow the dummy to move independent of the seatbelt, limiting the occupant movement. This can be seen in the dummy head movement comparison of the test data and the simulation for the right side occupant in the corkscrew test (Figure 20). In this research, we were primarily interested in the near-side occupant, so this model was useful for our purposes.

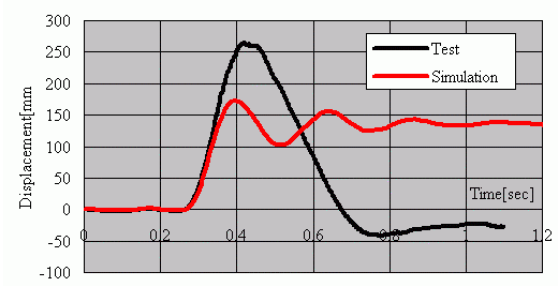

Figure20. Head movement of the far-side dummy in corkscrew type.

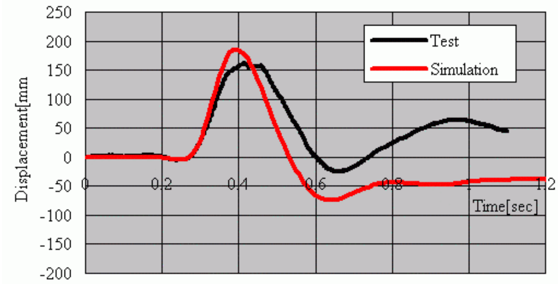

Figure21. Head movement of the near-side dummy in corkscrew type.

There were some inconsistencies also noted between the test and the simulation for the near side occupant's head displacement in the FMVSS 208 simulation. In the FMVSS 208 test the vehicle is initially positioned on the test dolly at an angle of 23 degrees, causing the influence of gravity to be shared between the vertical and lateral accelerations measured in vehicle local coordinate system. In the simulation the gravity was divided between the vehicle's vertical and lateral axis based on the initial roll angle being 23 degrees. However, the exact angle at rollover initiation may not be 23 degrees do to vibration during the acceleration portion of the test. This will result in errors be carried through the simulation due to the initial positioning of the vehicle not being accurate.

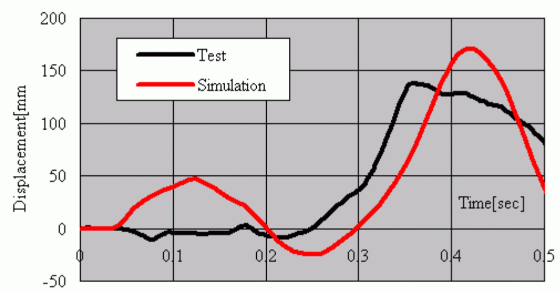

Figure22. Head movement of the near-side dummy in FMVSS208 type.

Overall, however, we believe the simulation and the test data correlated well, and simulation provides a good approximation of the occupant kinematics on the near side of a rollover for the first 90 degrees of the rollover.

- DIFFERENCES BETWEEN TRIP AND NON-TRIP EVENT

The test modes conducted for this research were classified as follows.

Trip-over: Curb Trip/Soil Trip/FMVSS208

Non-trip-over: SAE J857/Corkscrew/Ditch

In NASS, trip-over is described as ”Vehicle lateral motion that is resisted by a opposing force, inducing a roll moment.” In this testing, the rollover test types that would be classified as a trip-over are curb trip, soil trip, and FMVSS 208. The non trip-over tests consist of the SAE J857, corkscrew, and ditch tests. In the SAE J857 test, centrifugal force induced by the steering input and vertical force applied when the inner wheel goes over the ramp alone caused the test vehicle to rollover. In the corkscrew test, the vertical force applied by the ramp alone provided the roll moment to induce the vehicle to rollover.

In the ditch test, the steering input, and the influence of the slope provided the roll moment to induce the rollover.

We choose the SAE J857 test as the typical non-trip rollover, and the curb trip test as the typical trip-over rollover test for the purposes of this study. Figures 23 and 24 show the comparison between the head displacement and vehicle roll angle for each of these tests.

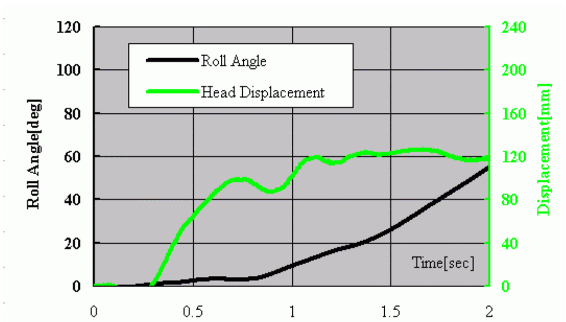

Figure23. Comparison between roll angle and head displacement in SAE J857 test type.

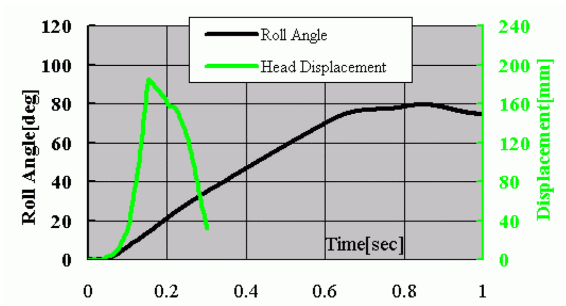

Figure24. Comparison between roll angle and head displacement in curb trip test type.

In the SAE J857 test, it took 1.296sec for the dummy’s head to displace 120mm, at the time when the vehicle’s roll angle was 18.3degree. On the other hand, in the curb trip test, it took only 0.136sec for the dummy’s head to displace 120mm, at the time when the vehicle had rolled 11.8degrees.

For rollovers with a large lateral acceleration (trip-over condition) the occupant displaces more quickly with respect to the roll angle than the occupant in a non trip-over rollover, SAE J857. In case of the ditch test, the occupant showed the same tendency as the SAE J857 test. In the initiation phase of the ditch rollover, only the centrifugal force that was generated by the steering input acted to displace the dummy. Whereas, in the case of the soil trip and FMVSS 208 tests, the dummy’s head moves to the vehicle outer direction faster than the SAE J857 or ditch test because of the lateral acceleration in initiation phase of the rollover. Therefore, the activation timing of the restraint system (seatbelt or airbag) is critical in a trip-over event.

In each of the tests in which the vehicle had a lateral acceleration acting on it, the dummies moved towards the roll direction. However in the corkscrew test, in which there was no lateral acceleration the dummy kinematics were unique. Since there was no lateral acceleration, as the vehicle entered the ramp the dummies tended to resist the motion of the vehicle due to their inertia, and remain in their initial position (with respect to the global coordinate system). Therefore, in a rollover toward the left side of the vehicle the occupants rotated toward the right side of the vehicle first (in the vehicle’s local coordinate system). Once the vertical force induced by the ramp was removed and only vehicle’s roll moment was acting on the occupants each moved toward the outboard sides of the vehicle.

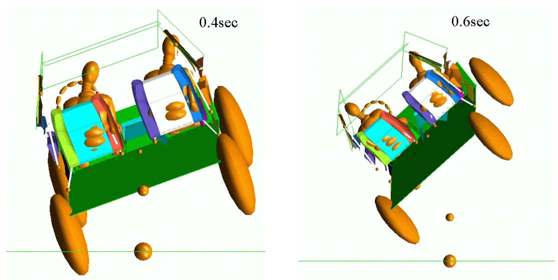

Figure25. Occupant behavior in corkscrew test.

CONCLUSION

The purpose of this research was as follows

- Construct a simulation model that can be used to accurately predict the occupants’ kinematics during the initial phase of a vehicle rollover that is relatively simple, to minimize computation time.

- Understand the differences in the occupant kinematics in the initial phase of the rollover depending on rollover initiation type.

The following observations were made considering these two purposes.

- The technique outlined in this paper to compensate for the effects of gravity in the test data, and use the compensated data as prescribed motion inputs for the MADYMO model allowed us to use a simplified model to analyze near side occupants' kinematics in rollover crashes.

- In the trip-over tests (curb and soil), there is a tendency that the near-side dummy head moved toward the roll direction before a significant roll angle was developed due to the vehicle's lateral acceleration.

- The occupant behavior in SAE J857 and Ditch tests is slower than the curt trip or soil trip test.

- In the corkscrew test, the occupants initially move away from the roll direction of the vehicle due to the dummies' inertia. Once the vertical force from the ramp is removed the dummies move toward the outside of the vehicle. (away from the center of the vehicle).

As mentioned, there are many types of rollovers that occur in the real world and the restraint system must be sufficient to provide reasonable occupant protection, which is the challenge in developing an adequate rollover protection system.

ACKNOWLEDGEMENTS

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